Optimization in Planning Construction Site Layouts

Réalisé par : Rhazouli Narjis
Encadré par : Mme. EL MKHALET Mouna

المدرسة المحمدية للمهندسين
Ecole Mohammadia d'Ingénieurs
جامعة محمد الخامس بالرباط
Université Mohammed V de Rabat

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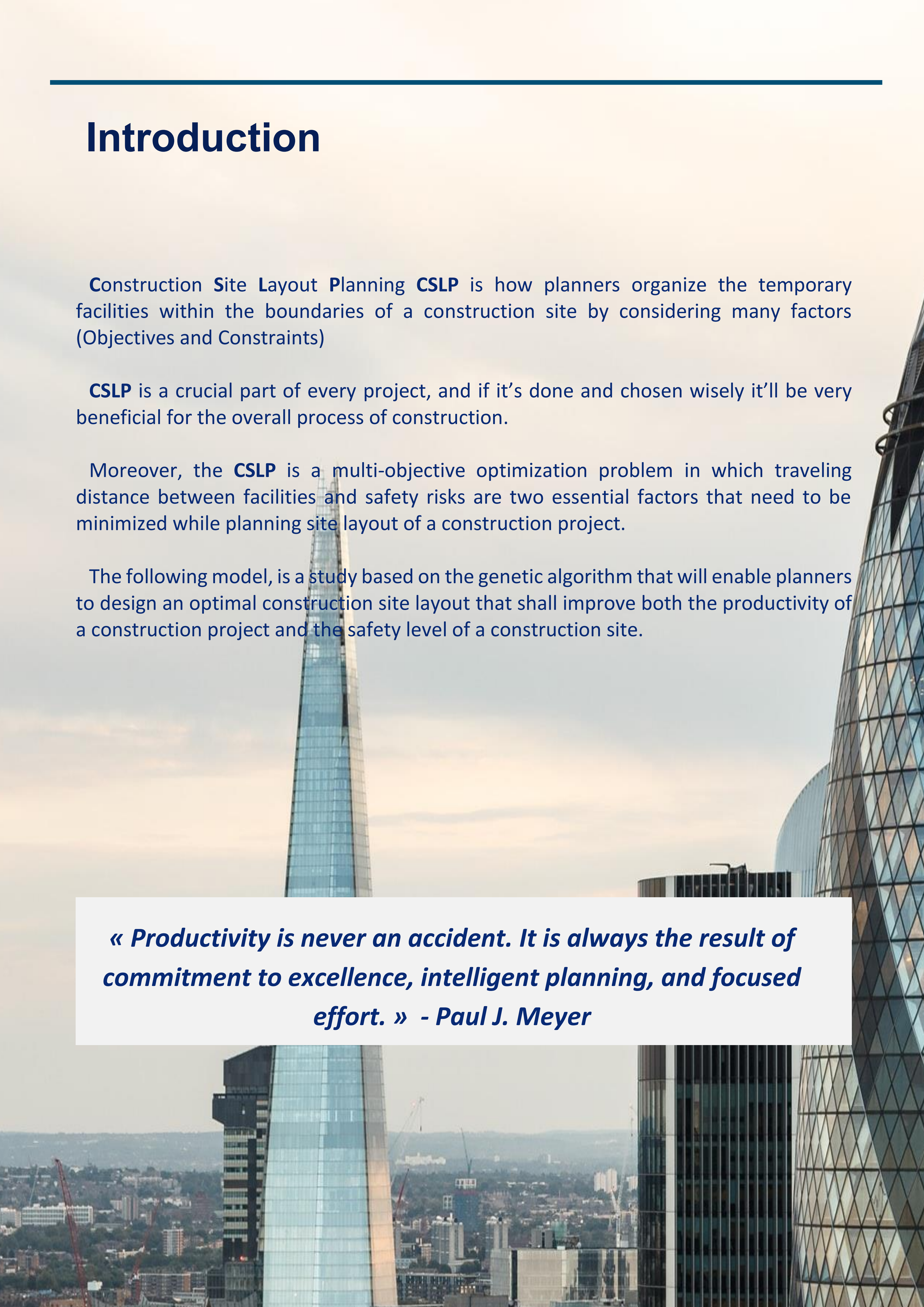


Introduction

Construction **S**ite **L**ayout **P**lanning **CSLP** is how planners organize the temporary facilities within the boundaries of a construction site by considering many factors (Objectives and Constraints)

CSLP is a crucial part of every project, and if it’s done and chosen wisely it’ll be very beneficial for the overall process of construction.

Moreover, the **CSLP** is a multi-objective optimization problem in which traveling distance between facilities and safety risks are two essential factors that need to be minimized while planning site layout of a construction project.

The following model, is a study based on the genetic algorithm that will enable planners to design an optimal construction site layout that shall improve both the productivity of a construction project and the safety level of a construction site.

> ***« Productivity is never an accident. It is always the result of commitment to excellence, intelligent planning, and focused effort. » - Paul J. Meyer***

Justifying the topic choice:

Construction site layout planning is a significant task in every construction project. The way you organize your construction site is very important since it affects the duration of the project and its overall cost.

In the absence of an effective and a systematic approach to site layout planning, construction projects especially those involving a high number of manpower, and equipment may face time loss, cost overruns and will decrease the construction site safety.

So, it is very important to choose the right layout solution for your construction site, and to do so an engineer must definitely know how to make the right and most optimal decisions.

This is why I decided to study such a topic, and chose the following model which is based on genetic algorithms to solve this multi-objective optimization problem.

Problematic:

Static or dynamic construction site layout planning is a multi-objective optimization problem; the two main objectives are to minimize the travel costs of resources in site and to maximize the safety of construction operation.

How can we find balance between cost and safety in planning construction site layouts?

How can we choose the optimal solution for construction site layout planning?

Solution:

Genetic algorithm, a trade-off between cost and safety in planning construction site layouts.

The model will be explained in details and more fully later in this report.

A detailed explanation of the solution

So, to put it in a simple way, our objective will be to develop a model that can simultaneously maximize the safety of construction operations and minimize the travel cost of resources in site. The following model is developed in 3 main phases:

1. **Formulating** decision variables and optimization **objectives**
2. Identifying and **satisfying** all practical **constraint**s in planning construction site layout
3. **Implementing** the model as a multi-objective genetic algorithm

Formulating decision variables and optimization objectives

This model is formulated to support construction planners in identifying optimal locations for all temporary facilities on construction (storage areas of material and equipment, stockpiles of excavation, site offices, fabrication shops, and batch plants). As such, the considered decision variables in the present model are the coordinates (Xi, Yi) of the center of gravity of each temporary facility i= 1 to I.

These variables are represented by an artificial genetic chromosome that depicts the coordinates (Xi, Yi) of each temporary facility i on site Fig. 1). The designed chromosome enables the present model to evaluate the impact of various site layout solutions S1 to SN on safety and travel costs of resources (Fig. 1).

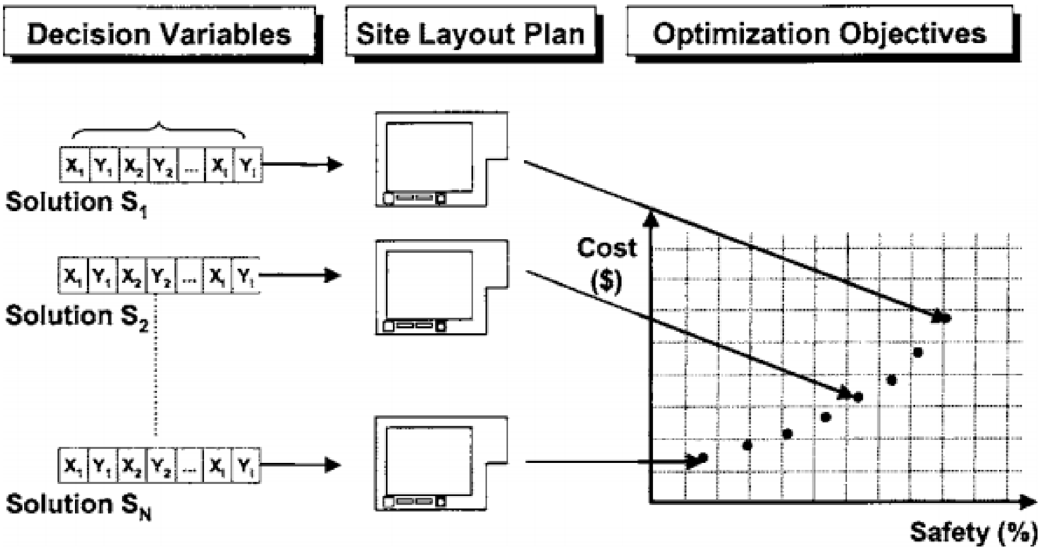

Decision Variables
Site Layout Plan
Optimization Objectives
X_1 Y_1 X_2 Y_2 ... X_I Y_I
Solution S_1
X_1 Y_1 X_2 Y_2 ... X_I Y_I
Solution S_2
X_1 Y_1 X_2 Y_2 ... X_I Y_I
Solution S_N
Cost ($)
Safety (%)

Fig. 1. Model formulation

1) Maximizing construction safety:

a) Safety of crane operations:

Cranes play an indispensable role in handling heavy material and equipment on construction sites, but available statistics indicate that cranes and falling objects are one of the leading causes of construction accidents.

The present model is designed to search for safe locations of temporary facilities in an attempt to minimize the risk of crane accidents and falling objects, especially on areas where construction workers and engineers are concentrated.

To do so we need to calculate a performance metric called the **C**rane **S**afety **C**riterion **CSC.**

The CSC helps planners to quantify the degree of safety for all occupants of temporary facilities on site according to their planned positions and exposure to falling objects from operating cranes as a function of:

- the sensitivity Vi of each temporary facility i to potential falling objects from cranes
- the distance dik between facility i and crane k (Fig. 2)
- the positioning of the facility either within the operating or nonoperating angles of the crane (Fig. 2).

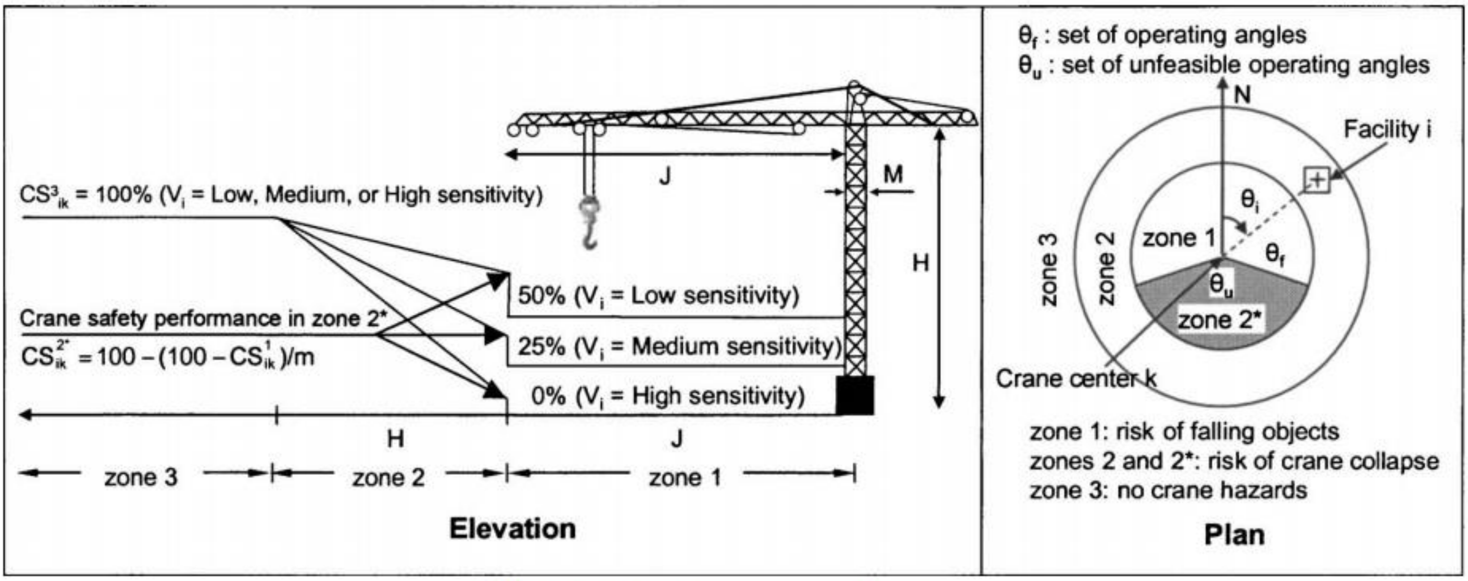

CS^3_{ik} = 100% (V_i = Low, Medium, or High sensitivity)
Crane safety performance in zone 2*
$CS^{2^*}_{ik} = 100-(100-CS^1_{ik})/m$
50% (V_i = Low sensitivity)
25% (V_i = Medium sensitivity)
0% (V_i = High sensitivity)
J
M
H
H
J
zone 3
zone 2
zone 1
Elevation
θ_f : set of operating angles
θ_u : set of unfeasible operating angles
N
Facility i
θ_i
θ_f
θ_u
zone 1
zone 2
zone 3
zone 2*
Crane center k
zone 1: risk of falling objects
zones 2 and 2*: risk of crane collapse
zone 3: no crane hazards
Plan

Fig. 2. Safety zones around cranes

$$\text{Crane safety criterion (CSC)} = \frac{\sum_{k=1}^{K} \frac{\sum_{i=1}^{I} (CS_{ik}^{z})}{I}}{K}$$

$$CS_{ik}^{z} = \begin{cases} CS_{ik}^{1} = \begin{cases} 0\% \ (V_i = \text{high}) \\ 25\% \ (V_i = \text{medium}) \\ 50\% \ (V_i = \text{low}) \end{cases} & \text{(Zone 1)} \\ CS_{ik}^{2^*} = 100 - \dfrac{100 - CS_{ik}^{1}}{m} & \text{(Zone } 2^*\text{)} \\ CS_{ik}^{2} = (100 - CS_{ik}^{2^*}) \left(\dfrac{d_{ik} - J - M/2}{H} \right) + CS_{ik}^{2^*} & \text{(Zone 2)} \\ CS_{ik}^{3} = 100\% \ (V_i = \text{high, medium, or low}) & \text{(Zone 3)} \end{cases}$$

where CS_{ik}^{z}=crane safety performance for temporary facility i due to its proximity to crane k in Zone z; V_i=sensitivity of facility i to falling objects; d_{ik}=distance between facility i and crane k; I=total number of facilities on site; K=total number of cranes on site; J=length of the crane jib; M=width of the crane mast; m=ratio between the risk of falling objects from crane and the risk of crane collapse; H=reach of the crane; θ_i=angle representing the location of temporary facility i measured clockwise from the north direction; θ_f=set of crane operating angles; and θ_u=set of unfeasible crane operating angles.

b) Control of hazardous material:

Hazardous materials (explosive devices, flammable materials, toxic substances…) need to be properly stored to minimize the risk of accidents on site.

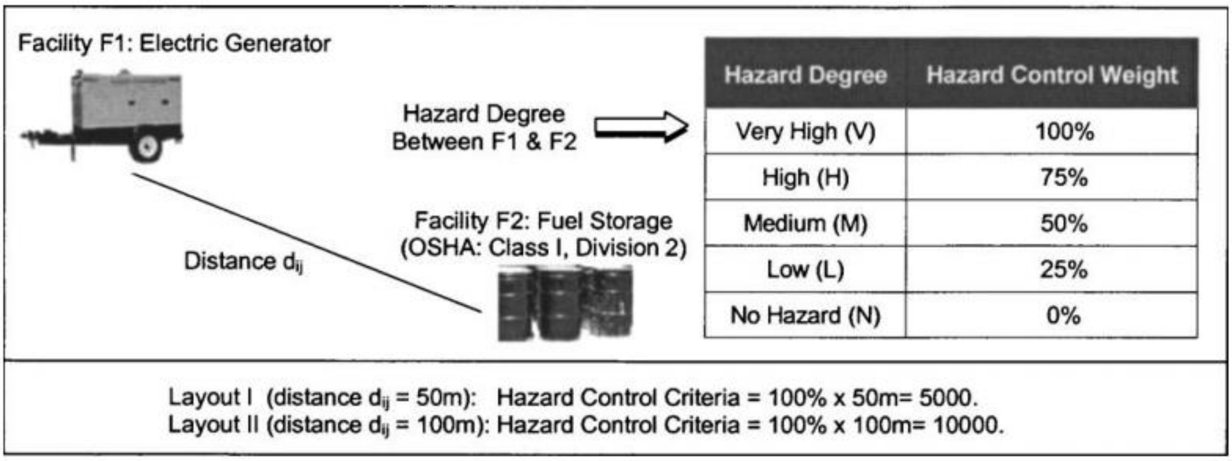
To quantify the degree of hazard control on site, we must calculate a performance metric called the Hazards Control Criterion **HCC.**

$$\text{Hazards control criterion (HCC)} = \sum_{i=1}^{I-1} \sum_{j=i+1}^{I} (\text{HCW}_{ij} \times d_{ij}) \qquad d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

Where HCWij= hazard control weight that represents the risk of accidents that can be encountered on site if facilities i and j are not adequately separated (Fig. 3), dij= separation distance between facilities i and j, (Xi ,Yi)=coordinates of center of gravity of facility i; (Xj, Yj)=coordinates of center of gravity of facility j, and I=total number of facilities on site**.**

In order to ensure consistency in performance measurement among all the safety criteria in the present model, each calculated HCC value is then normalized to generate a normalized performance metric **NHCC** that ranges from 0 to 100%.

$$\text{Normalized hazards control criterion (NHCC)} = \frac{\text{HCC} - \text{HCC}_{\text{min}}}{\text{HCC}_{\text{max}} - \text{HCC}_{\text{min}}}$$


Facility F1: Electric Generator
Hazard Degree Between F1 & F2
Facility F2: Fuel Storage (OSHA: Class I, Division 2)
Distance d_ij

Hazard Degree	Hazard Control Weight
Very High (V)	100%
High (H)	75%
Medium (M)	50%
Low (L)	25%
No Hazard (N)	0%

Layout I (distance d_{ij} = 50m): Hazard Control Criteria = 100% x 50m= 5000.
Layout II (distance d_{ij} = 100m): Hazard Control Criteria = 100% x 100m= 10000.

Fig. 3. Measuring the performance of hazard control on site

c) Travel routes intersections:

Frequent movements of resources (labor, material, and equipment…) on site often create safety hazards and accidents when the travel routes of these resources intersect.

In order to improve safety and minimize the risk of accidents, construction planners need to search for and identify site layout plans that minimize the total number of intersection points on site.

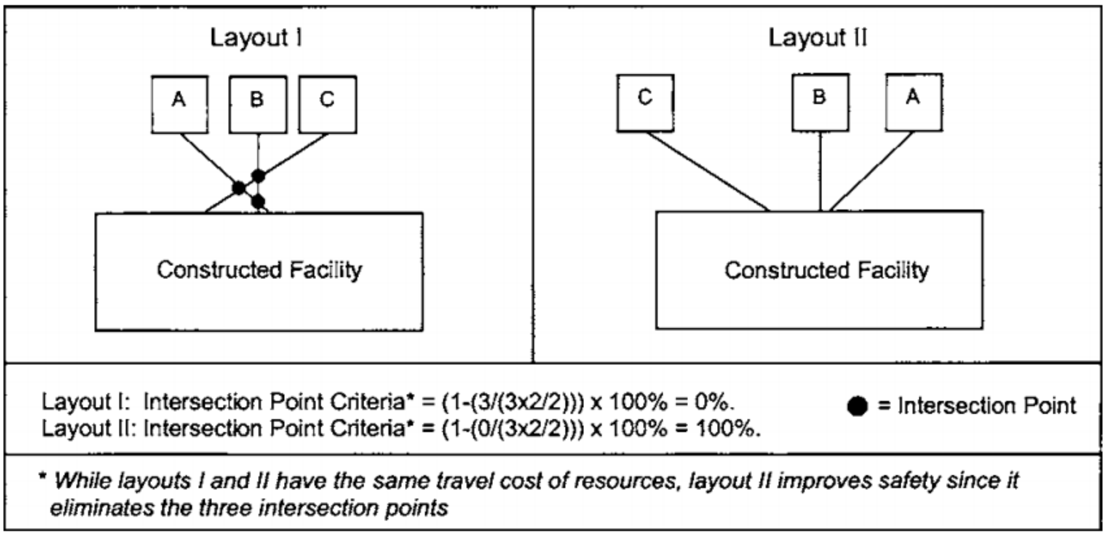
To do so we must calculate the **I**ntersection **P**oint **C**riterion **IPC** which enables planners to quantify the impact of intersections between heavily traveled routes on construction safety.

$$\text{Intersection point criterion (IPC)} = \left(1 - \frac{\text{IP}}{\text{IP}_{\text{max}}}\right) \times 100\%$$

$$\text{IP}_{\text{max}} = NR(NR - 1)/2$$

where IP=total number of intersection points on the generated site layout between all heavily traveled routes; IPmax=maximum possible number of intersection points between all heavily traveled routes; and NR=total number of heavily traveled routes on site.

In Fig. 4, Layout II provides an improved level of safety than that associated with Layout I as it eliminates the potential of accidents in intersection points on site, while providing the same travel distance and cost of resources on site.



Layout I: Intersection Point Criteria* = (1-(3/(3x2/2))) x 100% = 0%.
Layout II: Intersection Point Criteria* = (1-(0/(3x2/2))) x 100% = 100%.

* *While layouts I and II have the same travel cost of resources, layout II improves safety since it eliminates the three intersection points*

Fig. 4. Intersections among heavily traveled routes of resources

d) Overall construction site safety:

$$\text{Maximize construction safety} = \text{Maximize}\,[w_1 \times \text{CSC} + w_2 \times \text{NHCC} + w_3 \times \text{IPC}]$$

Where w1= relative weight or scaling constant of crane safety criterion; w2= relative weight or scaling constant of hazards control criterion; and w3= relative weight or scaling constant of intersection point criterion.

2) Minimize in site travel cost of resources:

$$\text{Minimize travel cost of resources} = \text{Minimize}\left[\sum_{i=1}^{I-1}\sum_{j=i+1}^{I}(C_{ij} \times d_{ij})\right]$$

$$d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \qquad C_{ij} = \sum_{r=1}^{R} \left(\frac{f_r \times c_r}{s_r} \right)$$

where Cij=travel cost rate in $/m of distance traveled between facilities i and j; dij= distance in meters between facilities i and j; (Xi ,Yi)=coordinates of center of gravity of facility i; (Xj,Yj)=coordinates of center of gravity of facility j; I=total number of facilities on site; fr= frequency of one-way traveling for construction crew r between facilities i and j during the lifecycle of the site layout plan; cr= hourly cost of traveling crew r in $/h; and sr= speed of traveling crew r in m/h

Identifying and satisfying all practical constraints in planning construction site layout

Two types of constraints are imposed:

- **Boundary constraints**: to ensure that temporary facilities are located within the site boundaries.
- **Overlap constraints**: to avoid the overlap of facilities on site.

1. Boundary constraints:

Boundary constraints are examined for each solution using the following four-step algorithm in order to ensure that each facility is located within the boundaries of the site:

- For each temporary facility i, find the coordinates of its center of gravity (Xi ,Yi), and its length in the X direction (Lxi) and width in the Y direction (Wyi)
- In the Y direction, examine the following two conditions: (1) the upper boundary of each facility (Yi+Wyi / 2) is less than the upper boundary of the site space (UY); and (2) the lower boundary of the facility (Yi−Wyi / 2) is greater than the lower boundary of the site space (LY), (Fig. 5)
- If both conditions in Step 2 are satisfied, perform a similar examination in the X direction
- If all the conditions in Steps 2 and 3 are satisfied, then facility i complies with boundary constraints. Otherwise, the solution is in violation of this type of constraint and therefore it should be precluded.

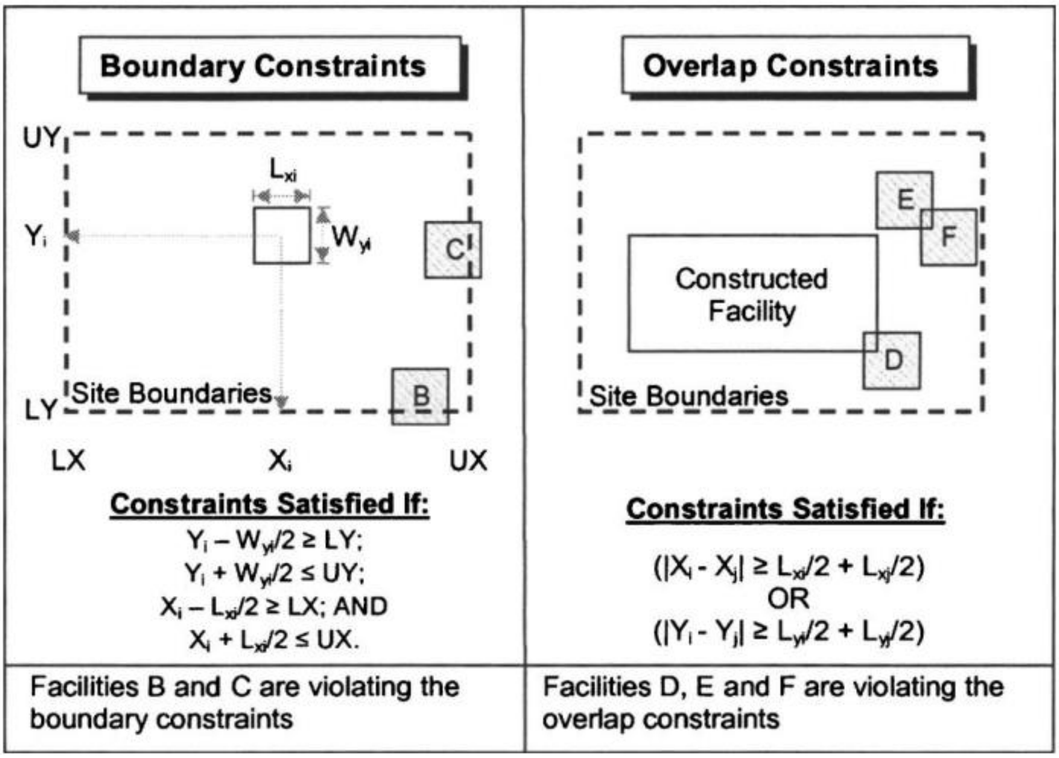

Boundary Constraints
UY
L_{xi}
Y_i
W_{yi}
C
LY
Site Boundaries
B
LX
X_i
UX
Constraints Satisfied If:
$Y_i - W_{yi}/2 \geq LY$;
$Y_i + W_{yi}/2 \leq UY$;
$X_i - L_{xi}/2 \geq LX$; AND
$X_i + L_{xi}/2 \leq UX$.
Facilities B and C are violating the boundary constraints
Overlap Constraints
E
F
Constructed Facility
D
Site Boundaries
Constraints Satisfied If:
$(|X_i - X_j| \geq L_{xi}/2 + L_{xj}/2)$
OR
$(|Y_i - Y_j| \geq L_{yi}/2 + L_{yj}/2)$
Facilities D, E and F are violating the overlap constraints

Fig. 5. Optimization constraints

2. Overlap contraints :

Overlap constraints are examined using the following four step algorithm:

- For each temporary facility i, find the coordinates of its center of gravity (Xi ,Yi) , and its length in the X direction (Lxi) and width in the Y direction (Wyi)
- To ensure that there are no overlaps between facilities i and j in the X direction, calculate the absolute difference between the X coordinates (Xi−Xj) of facilities i and j, and compare it to the average length of the two facilities in the X direction (Lxi /2+Lxj / 2). If (Xi−Xj >=Lxi /2+Lxj / 2) , then there is no overlap in the X direction
- Repeat Step 2 for the Y direction
- If overlaps are encountered in both Steps 2 and 3, then there is an overlap between the two facilities (Fig. 5), and therefore this solution should be precluded. Otherwise, overlap constraints are satisfied.

Model implementation

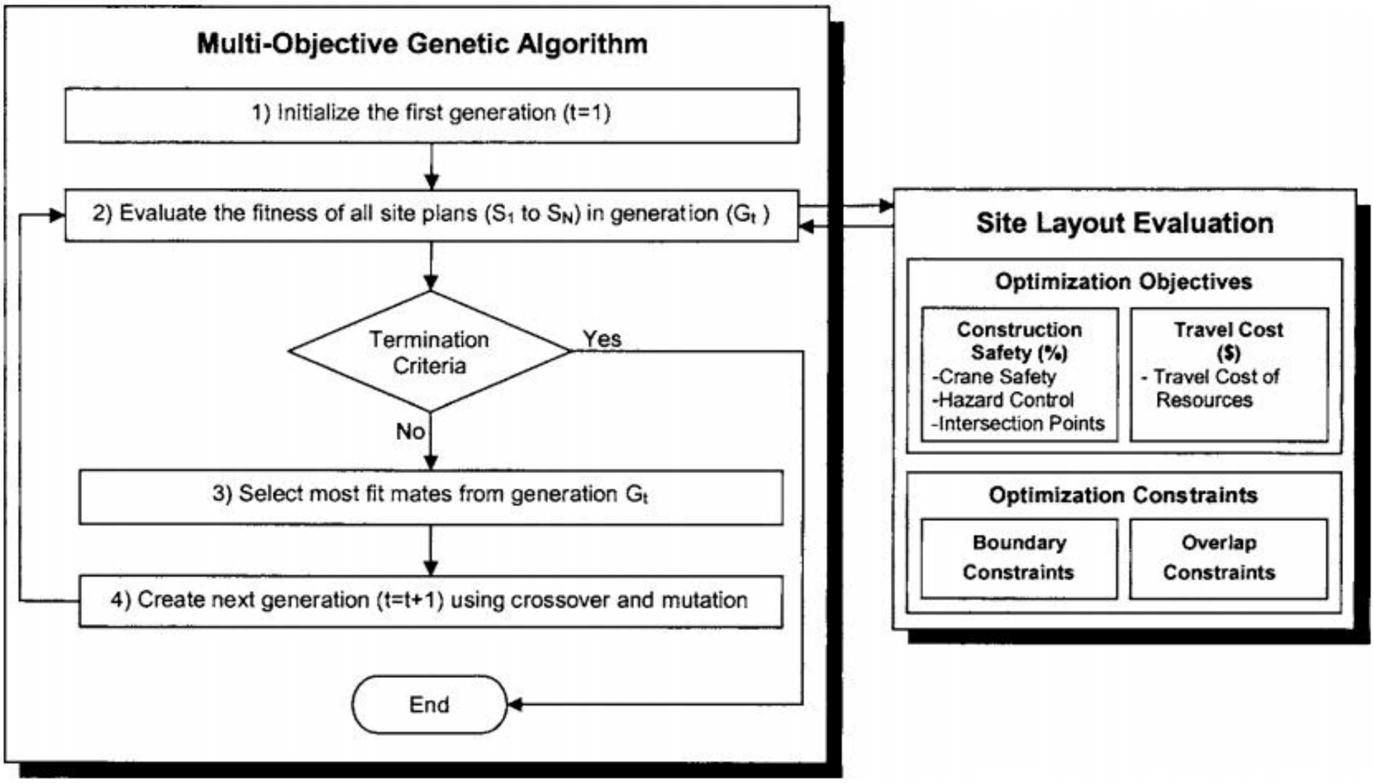

Multi-Objective Genetic Algorithm
1) Initialize the first generation (t=1)
2) Evaluate the fitness of all site plans (S₁ to Sɴ) in generation (Gₜ)
Termination Criteria
Yes
No
3) Select most fit mates from generation Gₜ
4) Create next generation (t=t+1) using crossover and mutation
End
Site Layout Evaluation
Optimization Objectives
Construction Safety (%)
-Crane Safety
-Hazard Control
-Intersection Points
Travel Cost ($)
- Travel Cost of Resources
Optimization Constraints
Boundary Constraints
Overlap Constraints

Fig. 6. Model implementation

The present model is implemented as a multi-objective genetic algorithm, in order to enable the generation of near optimal site layout plans that maximize construction safety and minimize travel cost of resources simultaneously, while satisfying all the practical layout constraints described earlier.

In order to achieve this, the model is implemented to perform the necessary computations (Fig. 6) in four major steps**:**

- ***Initialization of first generation:*** The genetic algorithm initializes the search and optimization process by randomly generating a set of N possible site layout solutions **(S1 ,S2 ,...,SN),** where each layout solution represents one possible arrangement for all facilities on site (Fig. 1). This initial set of site layout solutions represents the parent population in the first generation (G1) that evolves over T generations **(G1 ,G2 ,...,GT**) in an artificial process that simulates the evolution and natural selection theory.
- ***Evaluation of fitness function*****:** The algorithm evaluates the safety and cost performance of each possible site layout solution (Sn) in each generation (Gt) using the earlier described performance criteria. Based on the performance in these two optimization objectives, the algorithm calculates and assigns nondomination ranks

for each solution (Sn) in generation (Gt) . A solution is identified as "nondominated" if no other generated solution can provide better values for both construction safety and travel cost functions. Such nondominated site layout solutions are given rank 1, and the remaining solutions are given lower ranks based on their domination/nondomination by other solutions. These nondomination ranks are then used to represent the fitness of each solution for mating and reproduction in subsequent generations, as described in more detail in the next steps.

- ***Mating selection*:** The nondomination rank given by the algorithm to an individual solution of the population in the previous step is used to represent its fitness for survival and reproduction. In this process, site layout solutions with higher fitness are favored to be selected for reproduction in subsequent generations. Using a mating probability, the algorithm selects the most fit solutions from generation (Gt) to undergo reproduction according to their ranks, crowding distances, and constraints satisfaction
- ***Crossover and mutation:*** The most fit solutions selected in the previous step from generation (Gt) are then used to mate and reproduce a new set of N children site layout solutions using the genetic algorithm operators of crossover and mutation. First, a crossover operator is used to reproduce a new child site layout solution by swapping and exchanging chunks of the genetic data from two of the parent solutions. Second, a mutation operator is used to change the genetic materials in the strings randomly to maintain diversity in the population and to prevent immature convergence to inferior solutions. The fitness of the newly generated N children solutions is then evaluated using the earlier described procedure in the previous steps. The newly generated children solutions are then combined with their parents to form an expanded population of 2N individual solutions. From this expanded population, the most fit 50% of the solutions are chosen to survive and form the next generation (Gt+1) that will be used to reproduce new solutions in subsequent generations**.**

-- Steps 2, 3, and 4 are repeated over T generations (G1) to (GT) in order to generate a set of optimal site layout solutions. Each of these solutions describes the locations of all temporary facilities on site, and provides a unique trade-off between construction safety and the travel cost of resources on site (Figs. 1 and 7). As such, the present model enables construction planners to generate and evaluate optimal trade-offs between construction safety and cost.

So, the model can provide significant help to planners in selecting a site layout plan that provides the desired trade-off between safety and cost for the specific project being considered (Fig. 7).

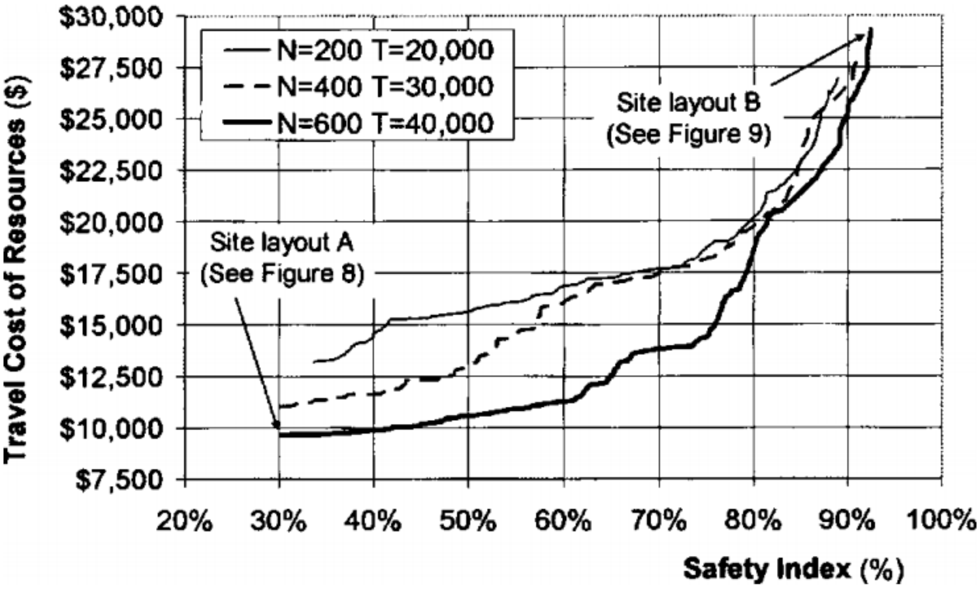


Fig. 7. Trade-off between construction safety and cost

Implementation in Morocco, Possible?

Using this model and applying the genetic algorithm is very useful to find a good balance between safety and cost in planning construction site layouts. Its application isn't that hard, once you identify and formulate your objectives and constraints all that's left is to apply the algorithm using a programming software such as MATLAB or Python to obtain the optimal solution for construction site layout planning problems.

Therefore, I don't see any obstacle that can prevent us from using such a method in Morocco or any other country. Once you understand the principle, and with some skills and intelligence an engineer can benefit from such algorithms to optimize different construction projects and find a trade-off between safety and cost in planning site layouts.

Moreover, this method is very advantageous since it treats the **CSLP** problem as a multi-objective optimization problem unlike many other studies that mainly focused on either diminishing the travel cost of resources on site without considering the safety aspect or vice versa.

And no matter how much this method will cost I think of it as a great investment since it will, on the other hand, reduce the traveling cost by a huge percentage and help to avoid accidents which is a gain with a great gab.

So, yes, this method can be and should be used in Morocco.

Enlargement perspectives:

Well from what we’ve seen, a well-planned construction site layout is fundamental for successful project as it enhances both productivity and safety of operations. So, indeed, CSLP (Construction Site Layout planning) should be studied carefully, but what’s more complicated than a CSLP is a dynamic CSLP. In fact, as construction evolves, the site layout may need to be dynamically reorganized at various schedule intervals to accommodate operational needs.

The dynamic Construction Site Layout Planning (DCLP) is a complex, combinatorial, multi-objective optimization problem which deals with the efficient arrangement of temporary construction facilities within a dynamically changing construction site considering, the characteristics of the facilities and their interrelationships, the characteristics of the construction site and the time-varying project needs.

So, the consideration of dynamic relocation of facilities from one project phase to another increases the problem size and, for this reason, a genetic algorithm can definitely be employed for the optimization as a result of its capabilities to tackle multi-objective optimization problems and to effectively search within a large solution space.

The efficiency of genetic algorithms has been proved by a number of case studies and operational scenarios. The results indicate that the algorithm response to **time-varying** input data is satisfactory in terms of solution quality and computation time.

So, Genetic algorithms can be used to solve complex optimization problems for dynamic construction site layouts planning. (road construction projects for example)

Who should be responsible for construction projects optimization?

I think that it’s wiser to assign the study of the optimal site construction layouts to a technical bureau (BET) because such a task falls within its specialty. In other words, the BET has special engineers that are well-trained and experienced when it comes to formulating and identifying problems, objectives and constraints, therefore the bureau is more capable of applying this genetic algorithm model.

On the other hand, the implementation of the optimal plans designed by the BET should be assigned to a big construction company.

Other Optimization methods used for CSLP

Ant Colony Optimization (ACO) for dynamic construction sites

With a simple mathematical procedure, it simulates the routes in a way that is used by ant colonies to find the best route while foraging for food: An ant that has discovered a short and efficient route will walk to and from the food source more frequently than ants that walk a longer route. The colony notices this by the pheromones emitted by the faster ant, and so can identify the quickest route without having to try each one. With the ant colony optimization algorithm, the computer learns how to think like an ant colony and can calculate the fastest route much quicker.

The Ant Colony Optimization algorithm can also be used on **Dynamic** construction site layout planning

Multi-objective Particle Swarm Optimization (MOPSO)

The idea is to move the swarm toward the optimal solutions. It considers a population of candidate solutions (particles) moving around in the search-space according to simple mathematical formula . Each particle's movement is influenced by its local best-known position, but is also guided toward the best-known positions in the search-space, which are updated as better positions are found by other particles.

The limitation of the model is that it produces solutions only for quadrilateral construction sites with one tower crane**.**

Conclusion

Optimization is crucial in every project.

As future engineers, our job is to find optimal solutions. Therefore, we must learn how to face optimization problems, and we should always aim for efficiency at lower cost.

And, as future civil engineers, adopting an efficient layout planning of a construction site is fundamental for successful project undertaking as it enhances both productivity and safety of operations.

Therefore, learning metaheuristic algorithms such as Genetic Algorithm and Ant Colony Algorithm is a precious advantageous skill.

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https://www.youtube.com/watch?v=1qpvpOHGRqA&t=774s
https://www.youtube.com/watch?v=qfeymoF8pb4

Particle swarm optimization:
https://www.youtube.com/watch?v=JhgDMAm-imI

Genetic algorithm:
https://www.youtube.com/watch?v=uQj5UNhCPuo&t=28s
https://www.youtube.com/watch?v=cxweR4i0ejA
https://www.youtube.com/watch?v=L--IxUH4fac